Compton polarimetry for the EIC

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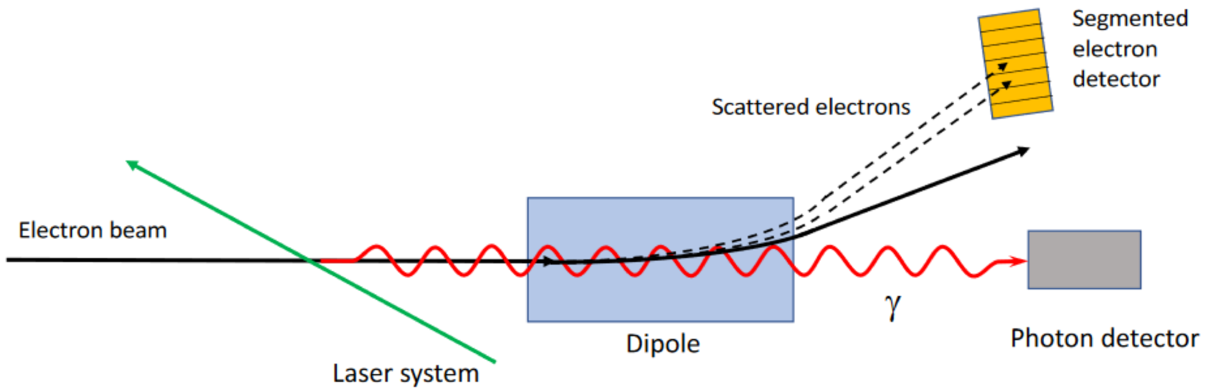
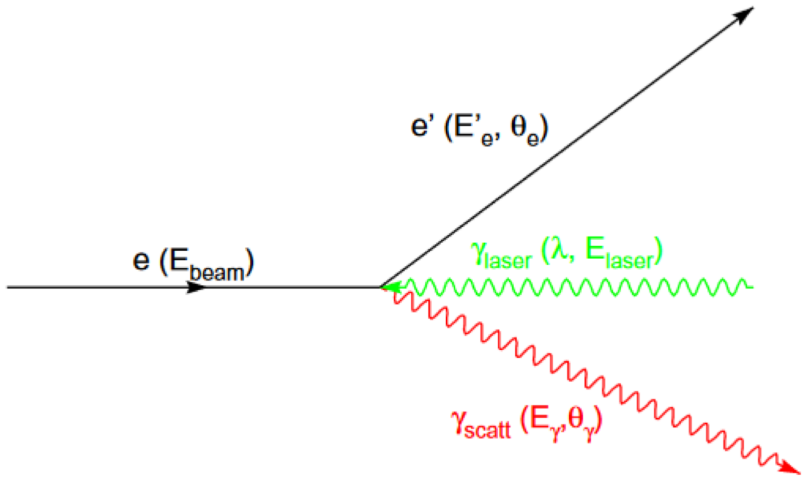
Compton polarimetry



Polarimeter	Energy	Sys. Uncertainty
CERN LEP*	46 GeV	5%
HERA LPOL	27 GeV	1.6%
HERA TPOL*	27 GeV	2.9%
SLD at SLAC	45.6 GeV	0.5%
JLAB Hall A	1-6 GeV	1-3%
JLab Hall C	1.1 GeV	0.6%

- Has seen extensive use in collider and fixed target facilities
  - Recent results have reached below 1% systematics at low energies (with electron measurements)
- It is an ideal candidate because of the non-destructive nature of the measurement

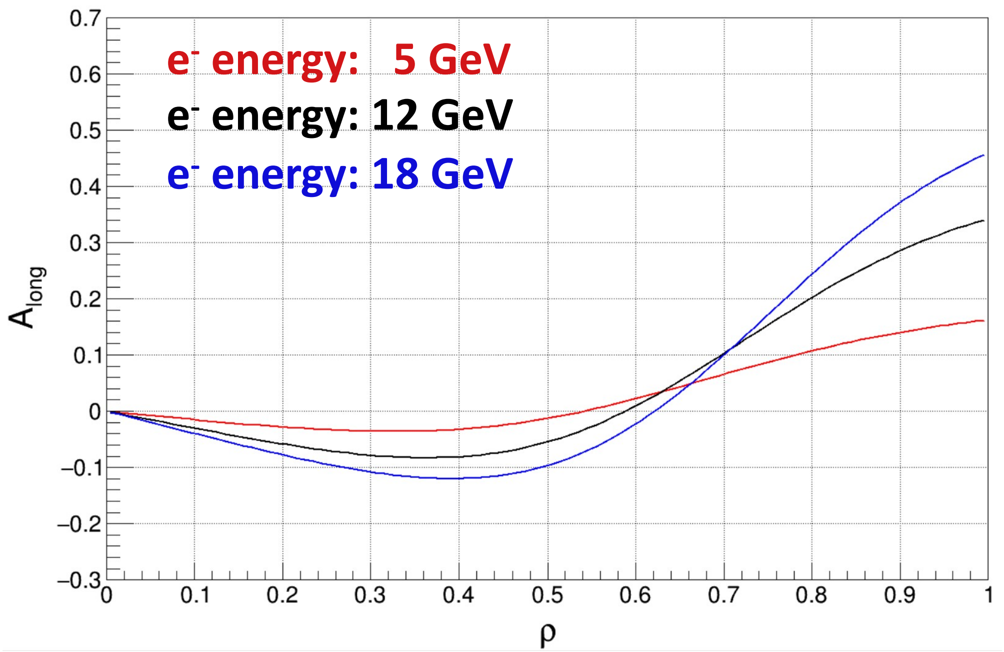


Compton polarimetry: measurement types

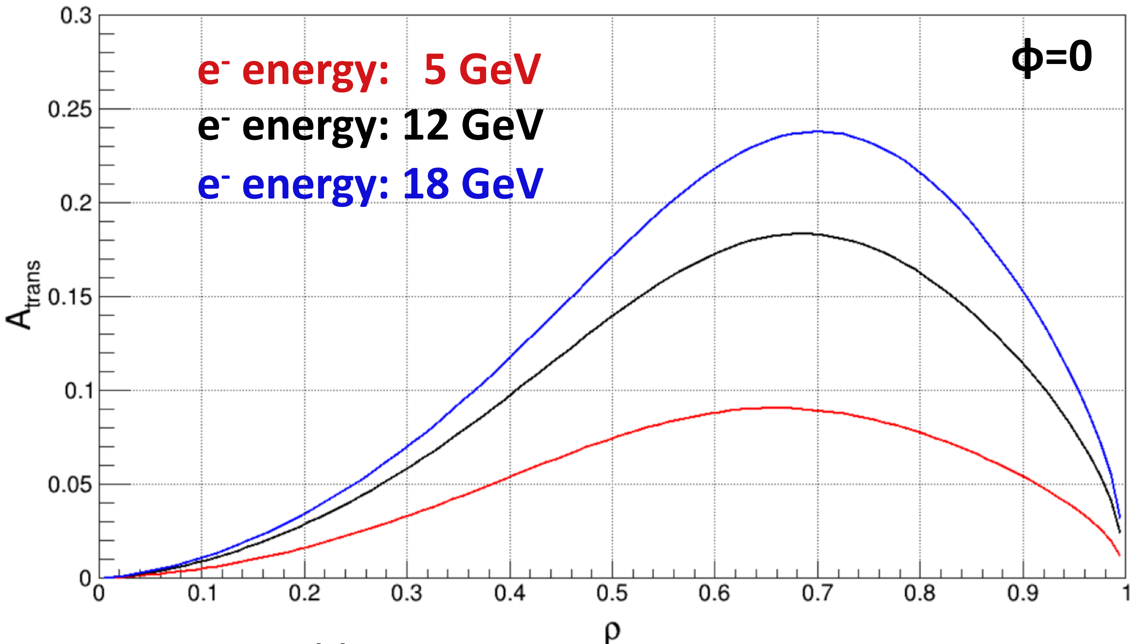
A. Single-photon mode
   - Detection event by event; improved precision through fit to energy distribution
   - Ideal for low background environments
B. Multi-photon mode (integrating)
   - The number of detected photons/electrons is measured
   - Will increase the S/B for situations when there is significant backgrounds
C. Energy weighted multi-photon mode (integrating)
   - The energy of the scattered particles has a linear relationship with measured quantity

Asymmetries for longitudinal and transverse polarimeters

$$A_{\mathrm{long}} = \frac{\sigma^{++} - \sigma^{-+}}{\sigma^{++} + \sigma^{-+}} = \frac{2\pi r_o^2 a}{(d\sigma/d\rho)}(1-\rho(1+a))\left[1 - \frac{1}{(1-\rho(1-a))^2}\right]$$



$$A_{\mathrm{tran}} = \frac{2\pi r_o^2 a}{(d\sigma/d\rho)} \cos\phi \left[\rho(1-a)\frac{\sqrt{4a\rho(1-\rho)}}{(1-\rho(1-a))}\right]$$

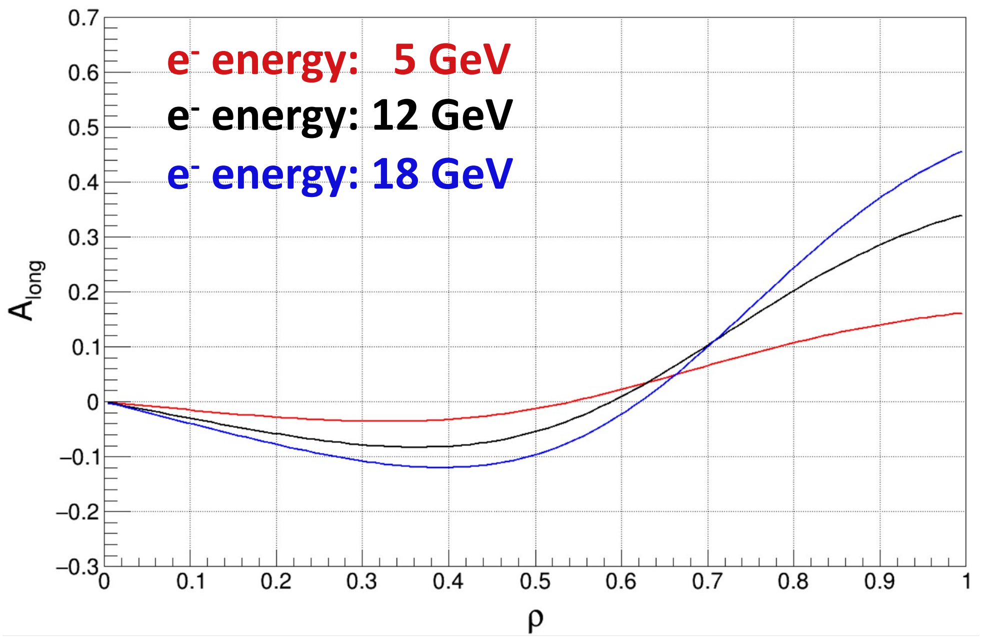


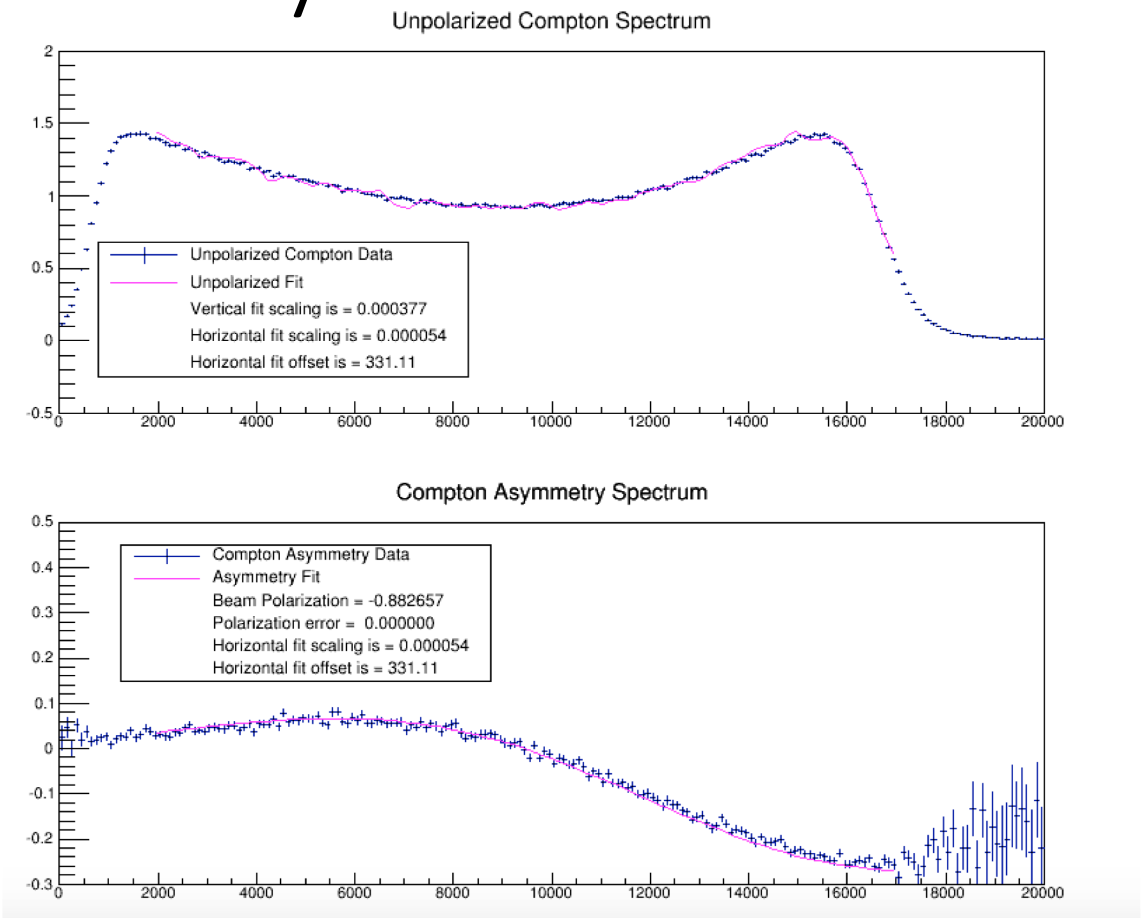
****Calculations based on 532nm laser system**

- For both the longitudinal and transverse polarimetry measurements at the at the energies of interested for the EIC the analyzing powers are significant

Longitudinal Compton polarimetry

$$A_{\mathrm{long}} = \frac{\sigma^{++} - \sigma^{-+}}{\sigma^{++} + \sigma^{-+}} = \frac{2\pi r_o^2 a}{(d\sigma/d\rho)}(1-\rho(1+a))\left[1 - \frac{1}{(1-\rho(1-a))^2}\right]$$



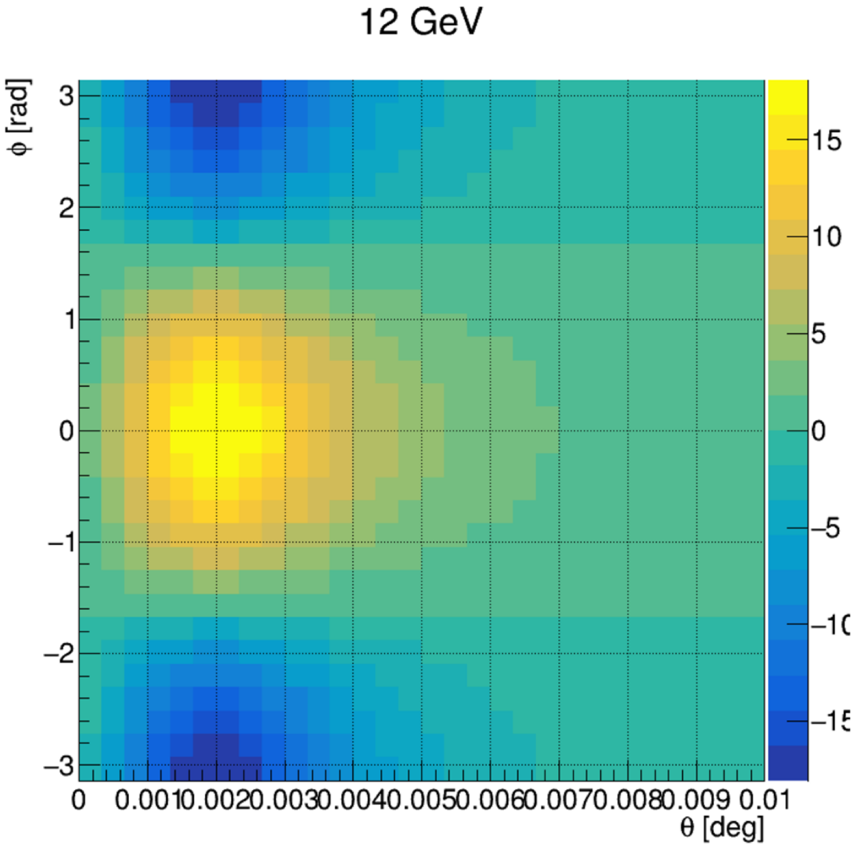


- Photon measurements can have large systematics due to detector response
- Best measurements achieved with electron detection
- At higher energies – spectrum threshold less important

HERA FP cavity-based LPOL achieved 0.9-1.1% precision with differential measurements in single-photon mode @ 27 GeV
→ Unlikely similar precision can be achieved at lowest energies envisioned for EIC

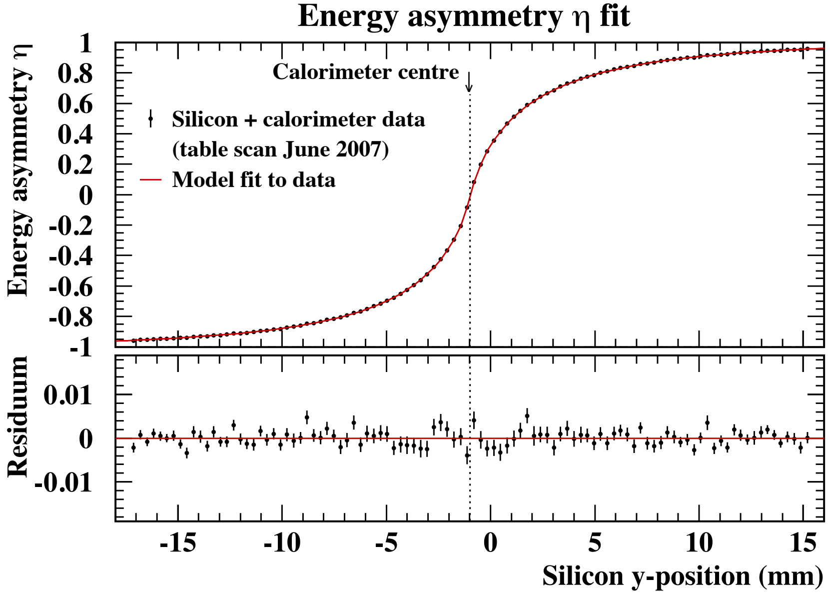
Transverse Compton polarimetry

$$A_{\text{tran}} = \frac{2\pi r_o^2 a}{(d\sigma/d\rho)} \cos\phi \left[\rho(1-a) \frac{\sqrt{4a\rho(1-\rho)}}{(1-\rho(1-a))} \right]$$



- Measurements are more challenging because you are looking at a position asymmetry

$$\eta = \frac{E_U - E_D}{E_U + E_D}$$



B. Sobloher et al, DESY-11-259 , arXiv:1201.2894

- HERA used a sampling calorimeter with top and bottom optically isolated: → Polarization measured via up-down energy asymmetry
- Strip detectors provide can be used to help calibrate the detector response
- With careful polarimeter design, high precision transverse measurements should be achievable

eRHIC specifications

- At 18 GeV bunches will be replaced every 6 min -> polarimetry measurement needs to happen in a much shorter time span
- The amount of electrons per bunch is fairly small ~24 nC → will need bright laser beam to obtain needed luminosity
- Distance between buckets is ~10ns → bunch by bunch measurement cannot be done with a CW laser without super fast detectors

Table 1: Maximum Luminosity Parameters

Parameter	**hadron**	**electron**
Center-of-Mass Energy [GeV]	104.9	
Energy [GeV]	275	10
Number of Bunches	1320	
Particles per Bunch [10^{10}]	6.0	15.1
Beam Current [A]	1.0	2.5
Horizontal Emittance [nm]	9.2	20.0
Vertical Emittance [nm]	1.3	1.0
Hor. β-function at IP β_x^* [cm]	90	42
Vert. β-function at IPβ_y^* [cm]	4.0	5.0
Hor./Vert. Fractional Betatron Tunes	0.3/0.31	0.08/0.06
Horizontal Divergence at IP [mrad]	0.101	0.219
Vertical Divergence at IP [mrad]	0.179	0.143
Horizontal Beam-Beam Parameter ξ_x	0.013	0.064
Vertical Beam-Beam Parameter ξ_y	0.007	0.1
IBS Growth Time longitudinal/horizontal [hours]	2.2/2.1	-
Synchrotron Radiation Power [MW]	-	9.18
Bunch Length [cm]	5	1.9
Hourglass and Crab Reduction Factor	0.87	
Luminosity [10^{34}cm-2sec-1]	1.05	

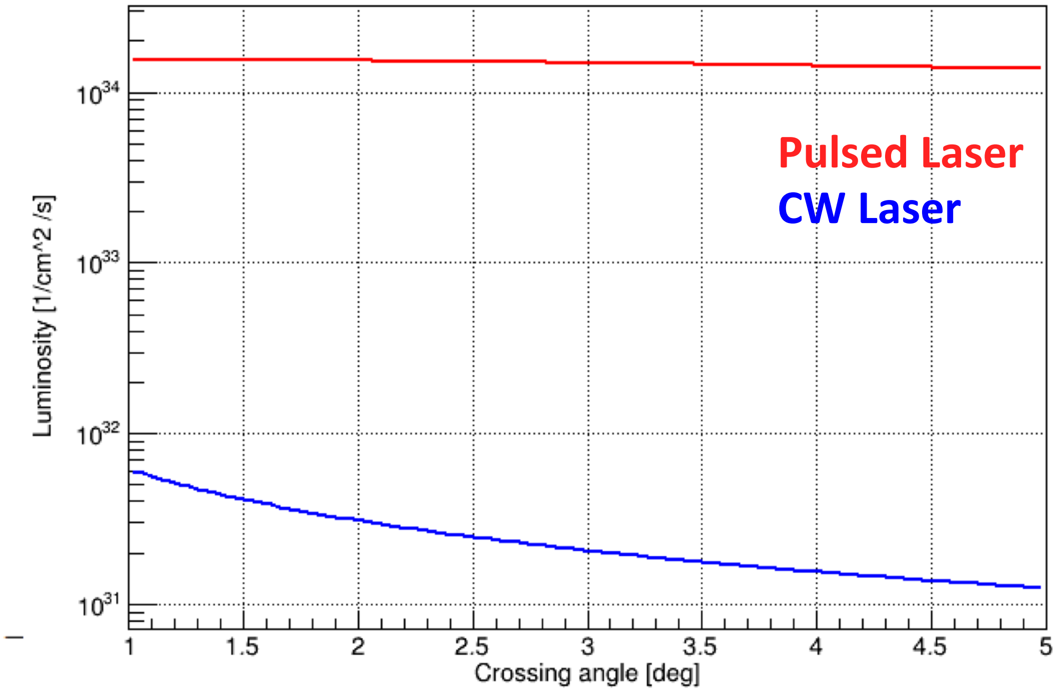
CW vs pulsed laser luminosity

- CW lasers could provide relative rapid measurements for average polarization of all bunches in ring
  - Bunch-by-bunch measurements challenging due to relatively small bunch spacing
- Pulsed system would allow straightforward identification of individual bunches AND improved luminosity
- Looking at a single bunch (with a beam frequency of ~78kHz) the luminosity for the same average power in the cavity (1kW) as a function of crossing angle shows a significant advantage for the pulsed cavity

- The conceived laser system has a repetition rate of 10MHz
  - Allow for simultaneous measurement of ~120 bunches, but leaving 100 ns between collisions for detector response
  - Shifting laser phase would allow measurement of all bunches

$$\mathcal{L}_{\rm CW} \approx \frac{1+\cos(\alpha_C)}{\sqrt{2\pi}\sin(\alpha_C)}\frac{I_e}{e}\frac{P_L\lambda}{hc^2}\frac{1}{\sqrt{\sigma_e^2+\sigma_\gamma^2}}$$

$$\mathcal{L}_{\rm pulsed} \approx \frac{1+\cos(\alpha_C)}{2\pi\sin(\alpha_C)}\frac{I_e}{e}\frac{c}{f_{beam}}\frac{P_L\lambda}{hc^2}\frac{1}{\sqrt{\sigma_e^2+\sigma_\gamma^2}}\left(\sigma_{e,z}^2+\sigma_{\gamma,z}^2+\frac{\sigma_e^2+\sigma_\gamma^2}{\sin^2(\alpha_c/2)}\right)^{-}$$

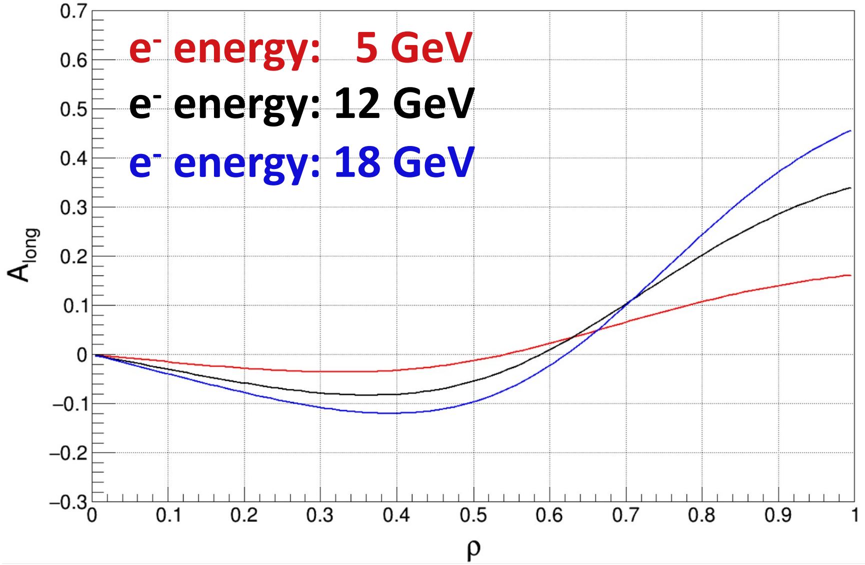


Time estimations: longitudinal

$$t_{meth} = \left(\mathcal{L}\,\sigma_{\mathrm{Compton}}\;\mathrm{P_e^2 P_\gamma^2}\;\left(\frac{\Delta \mathrm{P_e}}{\mathrm{P_e}}\right)^2\;\mathrm{A^2_{meth}}\right)^{-1}$$

A_{meth}

Single-photon	**Integrating**	**Energy Integrating**
$\langle \mathrm{A}^2 \rangle$	$\langle \mathrm{A} \rangle^2$	$\dfrac{\langle \mathrm{E} \cdot \mathrm{A} \rangle^2}{\langle \mathrm{E}^2 \rangle}$



beam energy [GeV]	$\langle A^2_{\mathrm{long}} \rangle$	t[s]	$\langle A_{\mathrm{long}} \rangle^2$	time [ms]	$\frac{\langle \mathrm{E \cdot A} \rangle^2}{\langle \mathrm{E}^2 \rangle}$	time [ms]
5	0.0061	29	0.0012	166	0.0022	88
12	0.0244	7	0.0033	69	0.0064	36
18	0.0414	4	0.0041	63	0.0085	30

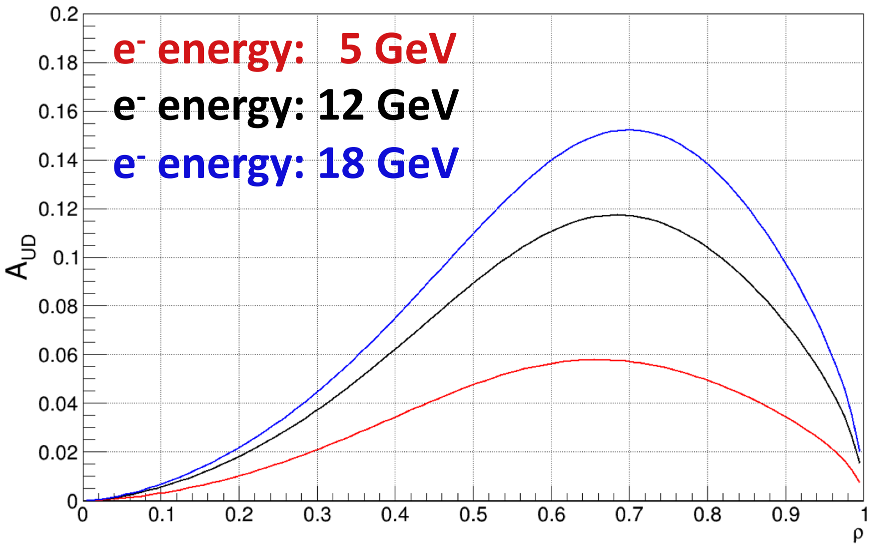
- Differential measurement assumes 1 photon/electron per crossing
  - The power needed for the laser system is approximately 1W
- The integrated method accepts the entire luminosity of the pulsed system (note the change in unit)
- Measurement times for all bunches in ring about 10 times longer

Time estimations: transverse

$$t_{meth} = \left(\mathcal{L}\ \sigma_{\mathrm{Compton}}\ \mathrm{P_c^2 P_\gamma^2} \left(\frac{\Delta \mathrm{P_c}}{\mathrm{P_e}} \right)^2 \mathrm{A^2_{meth}} \right)^{-1}$$

$$A_{meth}$$

Single-photon	**Integrating**	**Energy Integrating**
$\langle \mathrm{A}^2 \rangle$	$\langle \mathrm{A} \rangle^2$	$\frac{\langle \mathrm{E} \cdot \mathrm{A} \rangle^2}{\langle \mathrm{E}^2 \rangle}$

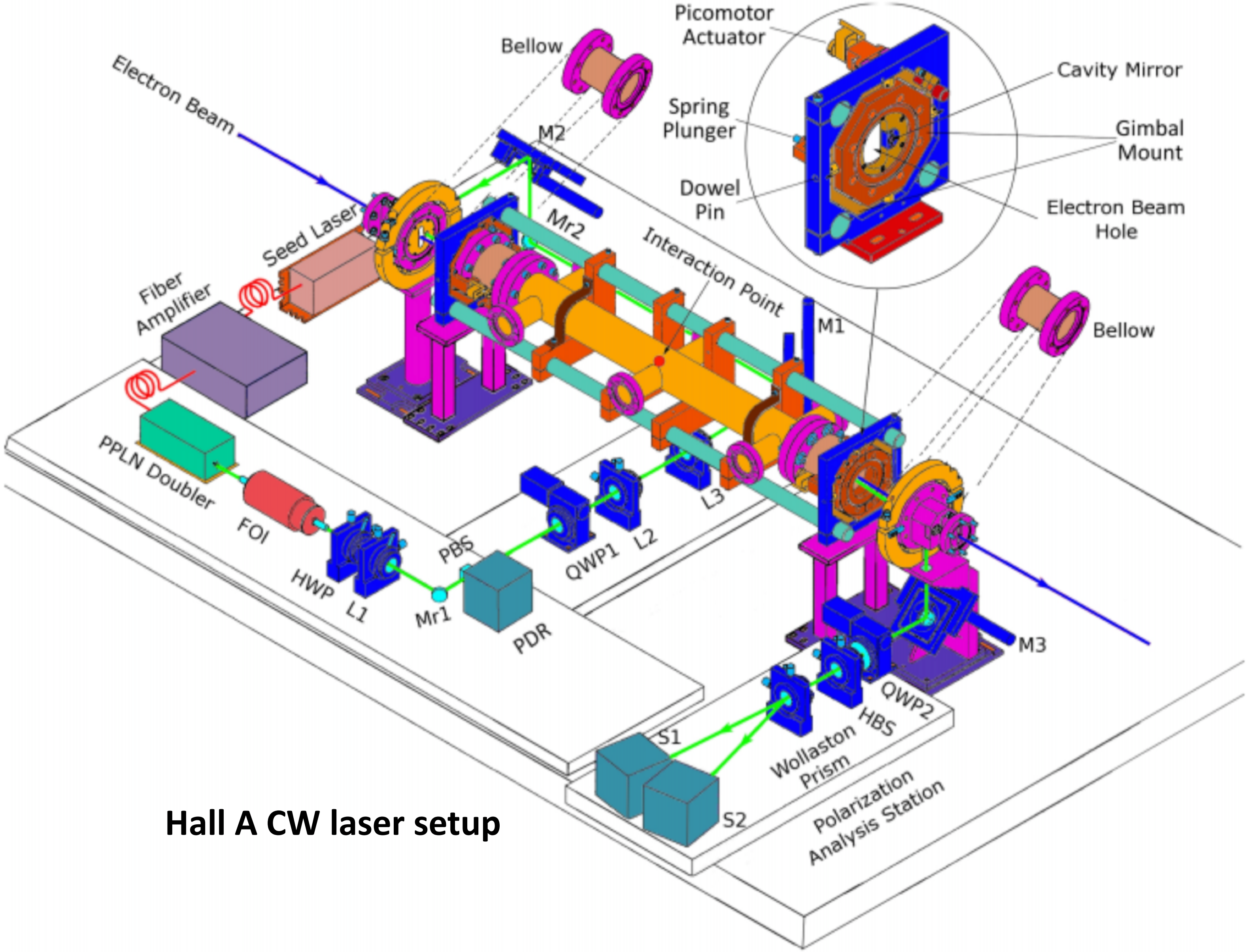


beam energy [GeV]	$\langle A^2_{\mathrm{UD}} \rangle$	t[s]	$\langle A_{\mathrm{UD}} \rangle^2$	time [ms]	$\frac{\langle \mathrm{E \cdot A} \rangle^2}{\langle \mathrm{E}^2 \rangle}$	time [ms]
5	0.0012	144	0.0008	234	0.0005	352
12	0.0048	365	0.0032	72	0.0019	123
18	0.0080	222	0.0052	49	0.0028	92

- Differential measurement assumes 1 photon/electron per crossing
  - The power needed for the laser system is approximately 1W
- The integrated method accepts the entire luminosity of the pulsed system (note the change in unit)

Proposed R&D

- We'd like to focus this R&D effort on developing a pulsed cavity with a large average power and large frequency
- Additionally we'd like to increase the robustness of the system by having rad-soft items (like seed laser and amplifier) at a large distance from the cavity itself
- Ideally we'd be able to test the system at CEBAF in hall A or hall C



Hall A CW laser setup

Laser system development

Initial laser development in lab

- Key Equipment required:
  - *Mode-locked laser*. Fiber amplifier and PPLN crystal also required for green laser.
  - Low-loss mirrors, cavity electronics
  - Some of the above may be borrowed from collaborating institutions

Deployment in beamline

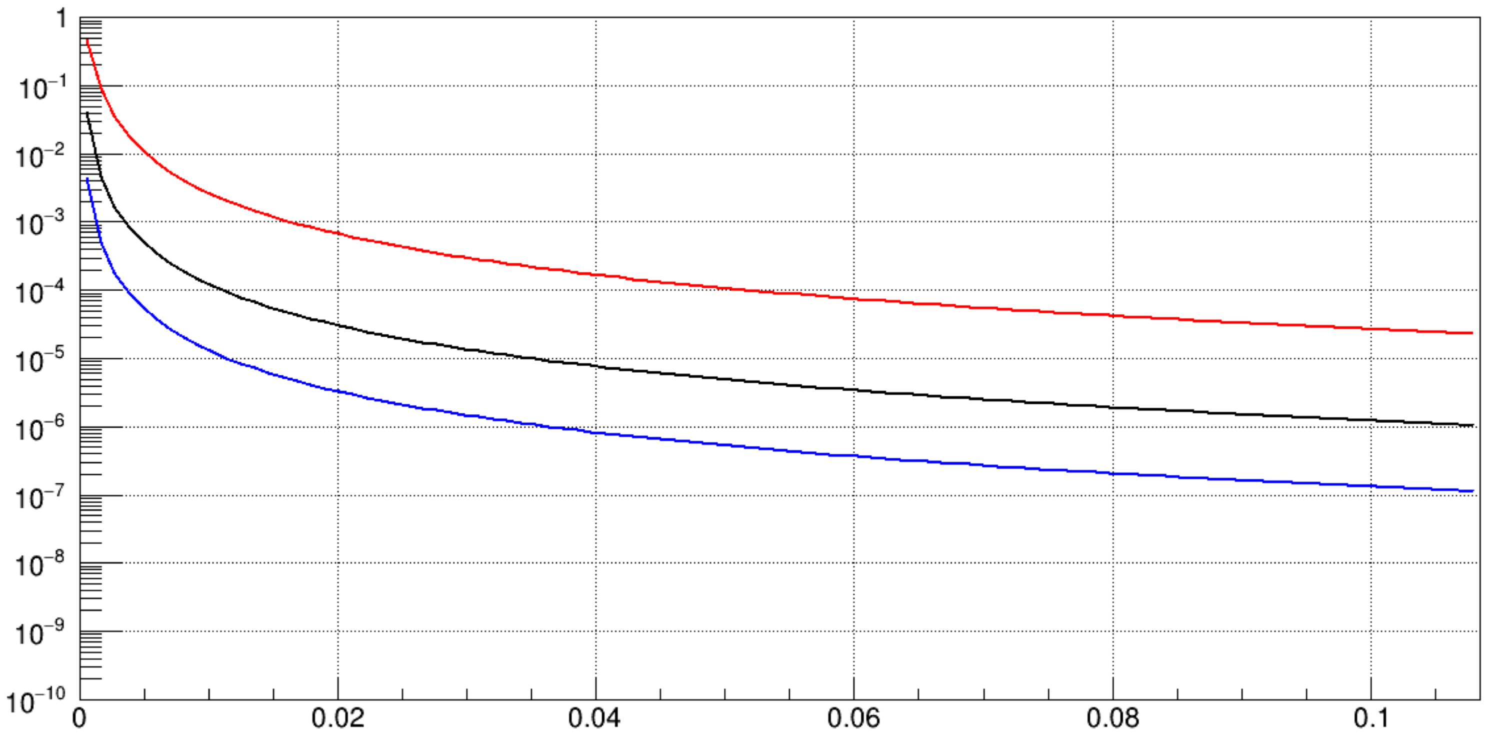
- Could be deployed in either Hall A or C at JLab
- Would require some modification of interaction region/vacuum system
  - Existing system somewhat modular, so modifications could possibly be done relatively cheaply
- Test with beam to verify ability to synchronize laser pulses with beam RF time

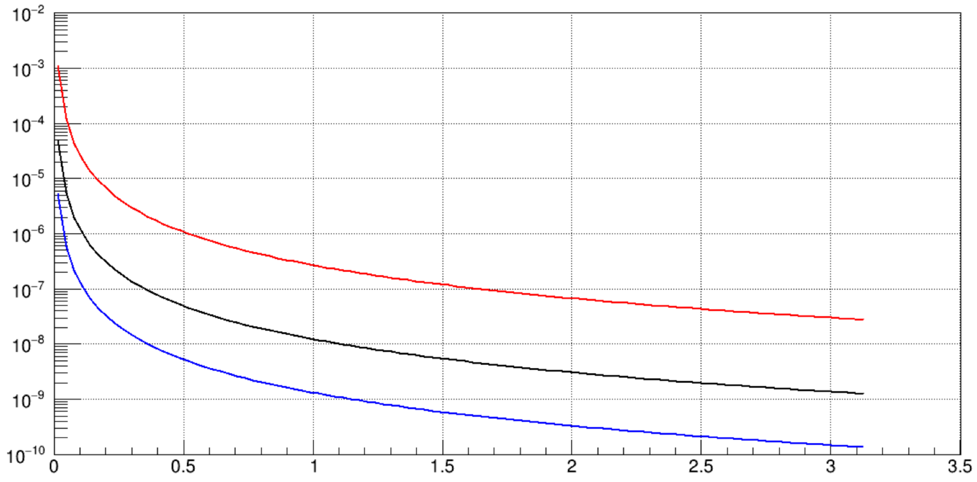
Conclusions

- Pulsed cavity is desirable to be able to make precise polarization measurements of each electron bunch rapidly
- A pulsed laser system allows straightforward measurement of the bunch-by-bunch electron polarization without the need for very fast detectors
- CW Fabry-Perot cavities relatively common in accelerator environment – pulsed cavity requires R&D and testing

Backup

Rho dependence on angle for 1, 5, 18 GeV (532 nm)

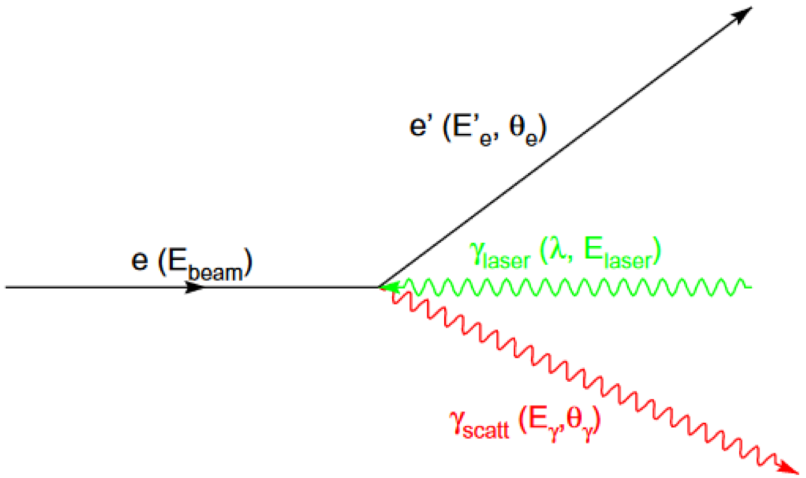




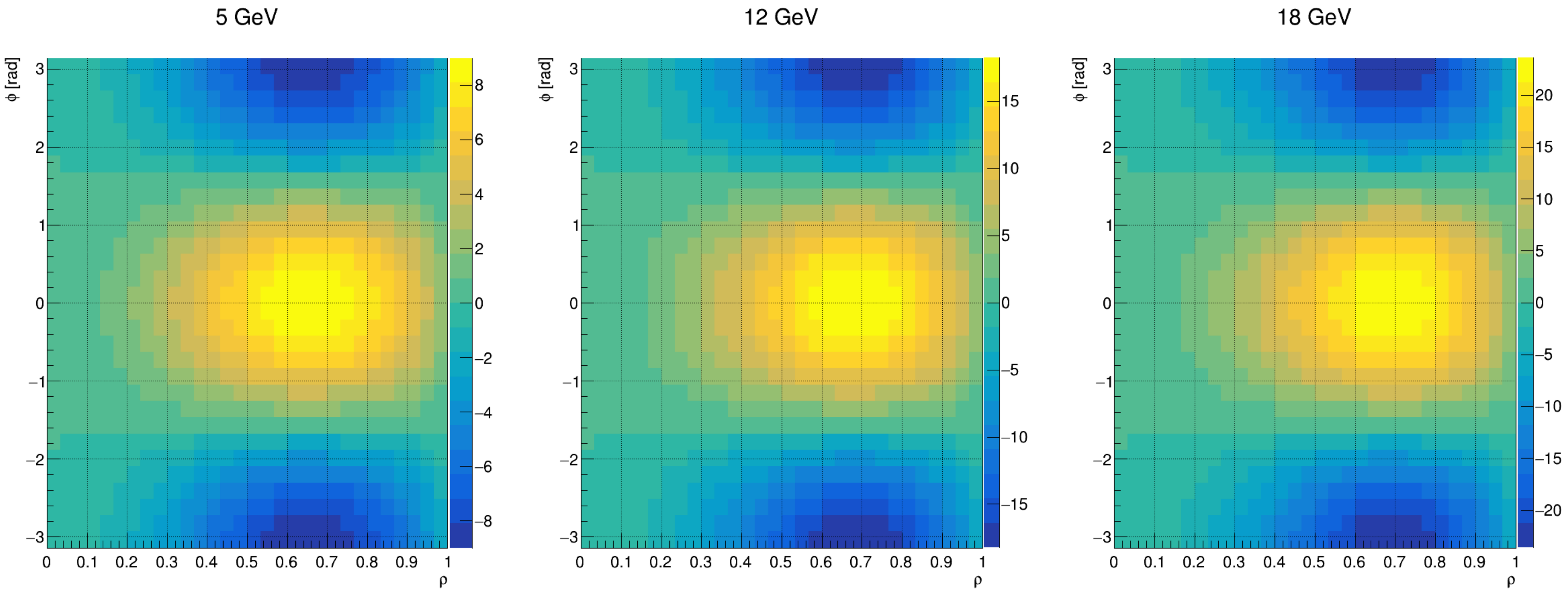
$$E_\gamma \approx E_{\text{laser}} \frac{4a\gamma^2}{1 + a\theta_\gamma^2\gamma^2},$$

$$E_\gamma^{\max} = 4aE_{\text{laser}}\gamma^2.$$

$$\rho = E_\gamma / E_\gamma^{\max} \qquad a = \frac{1}{1 + 4\gamma E_{\text{laser}}/m_e}.$$

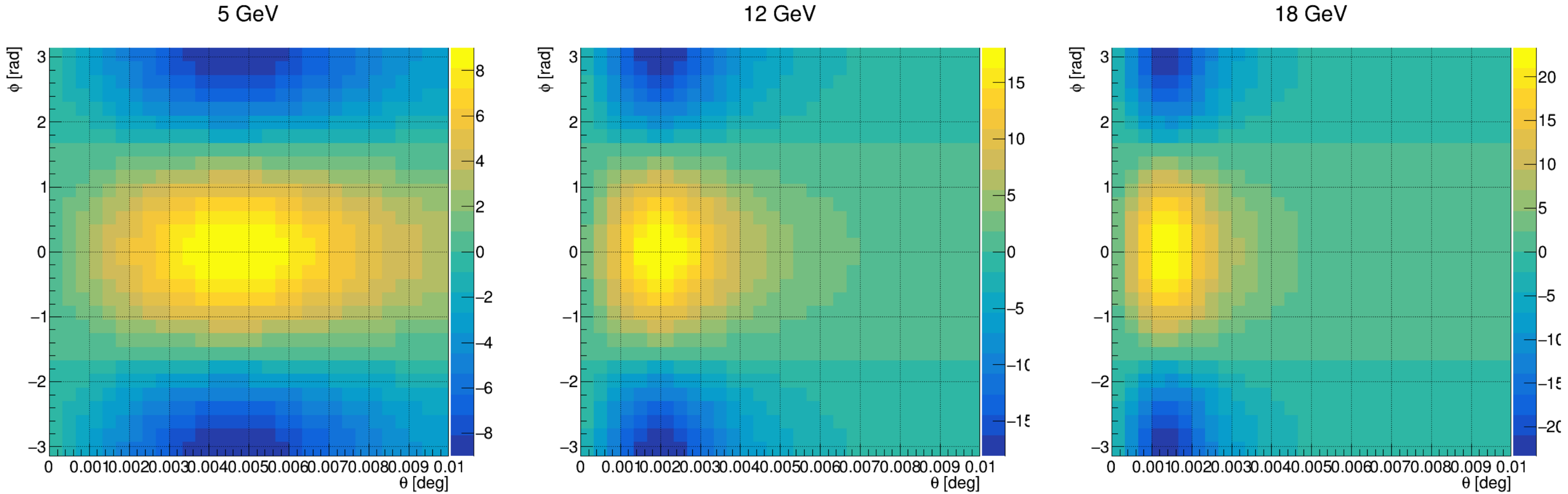


Atrans for 1, 5, 18 GeV (532 nm)



$$A_{\rm tran} = \frac{2\pi r_o^2 a}{(d\sigma/d\rho)} \cos\phi \left[\rho(1-a) \frac{\sqrt{4a\rho(1-\rho)}}{(1-\rho(1-a))} \right].$$

Atrans for 1, 5, 18 GeV (532 nm)



$$A_{\mathrm{tran}} = \frac{2\pi r_o^2 a}{(d\sigma/d\rho)} \cos\phi \left[\rho(1-a) \frac{\sqrt{4a\rho(1-\rho)}}{(1-\rho(1-a))} \right].$$

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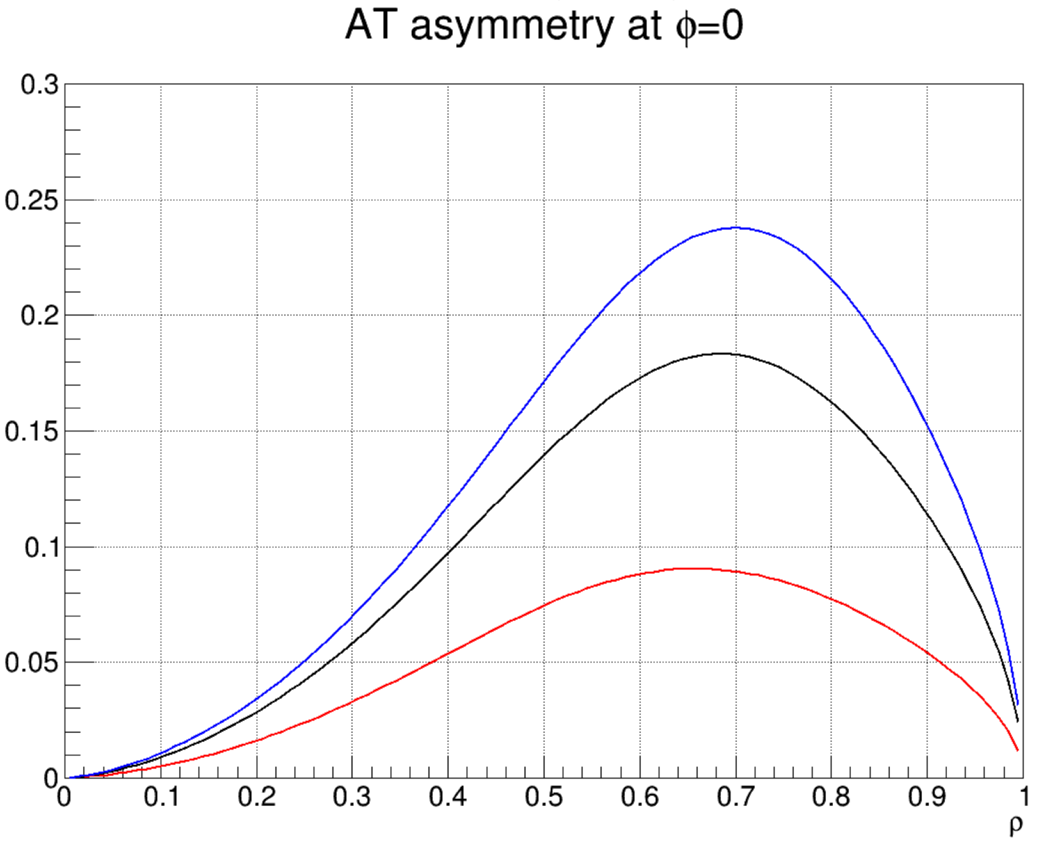

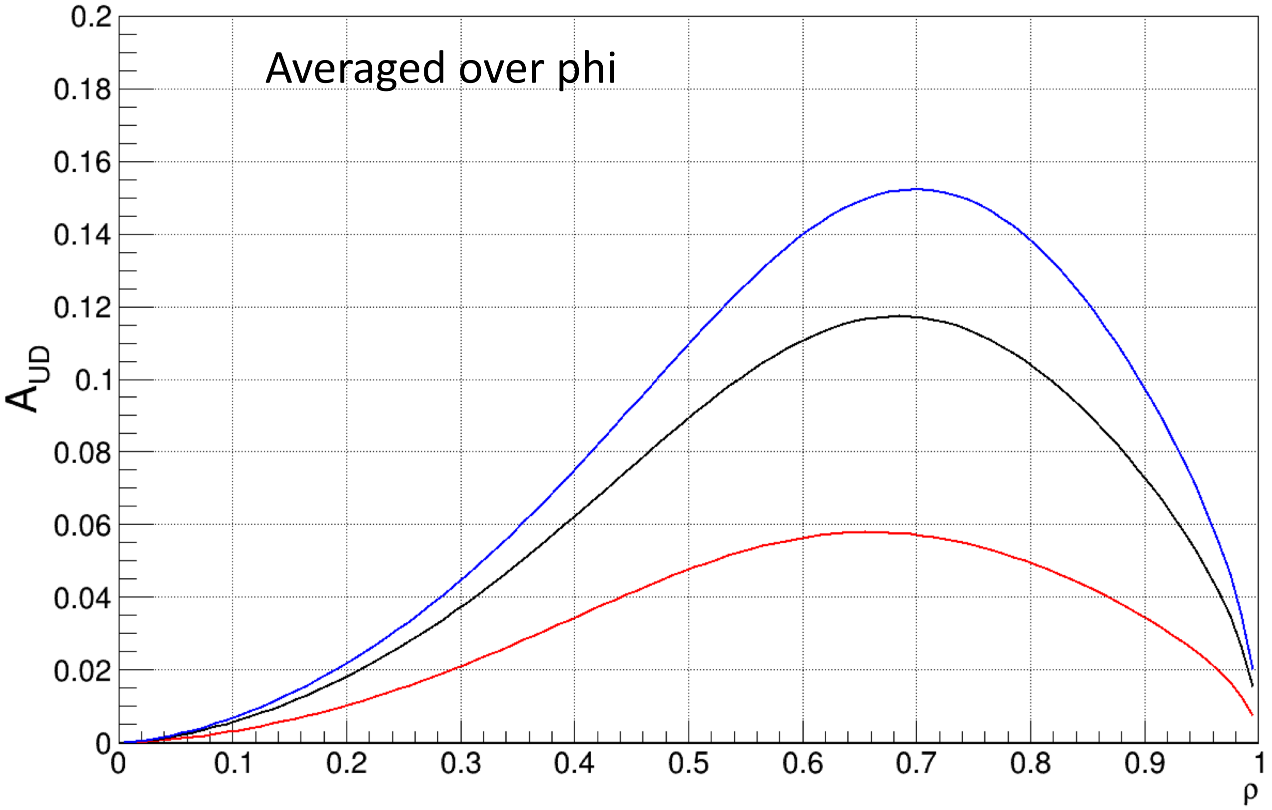

$$A_{\mathrm{tran}} = \frac{2\pi r_o^2 a}{(d\sigma/d\rho)} \cos\phi \left[\rho(1-a) \frac{\sqrt{4a\rho(1-\rho)}}{(1-\rho(1-a))} \right].$$